

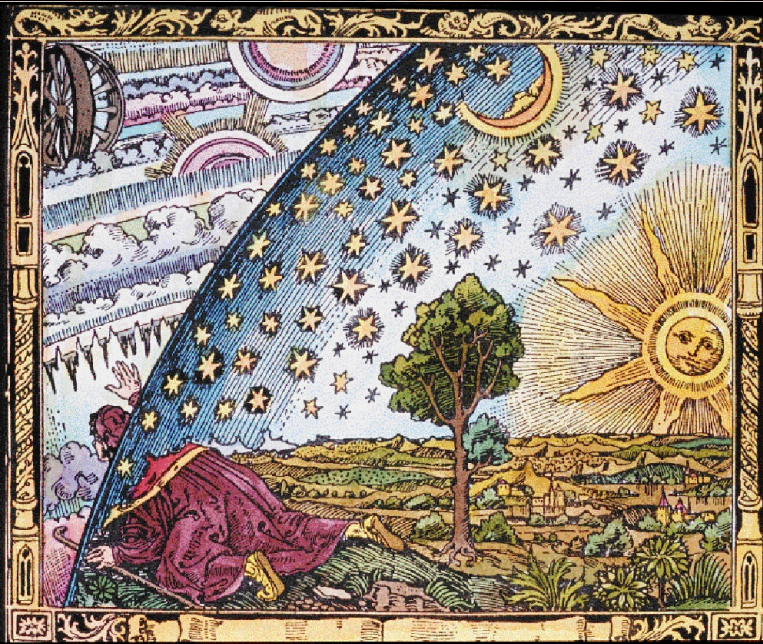
# A Quantum Journey



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# a World View



Nature is a fantastic **work of art**

It **inspires us** to think beyond ourselves

**We ask (Gauguin):** where do we come from? What are we? Where are we going?

Where does the Universe come from?  
What is it? Where is it going?



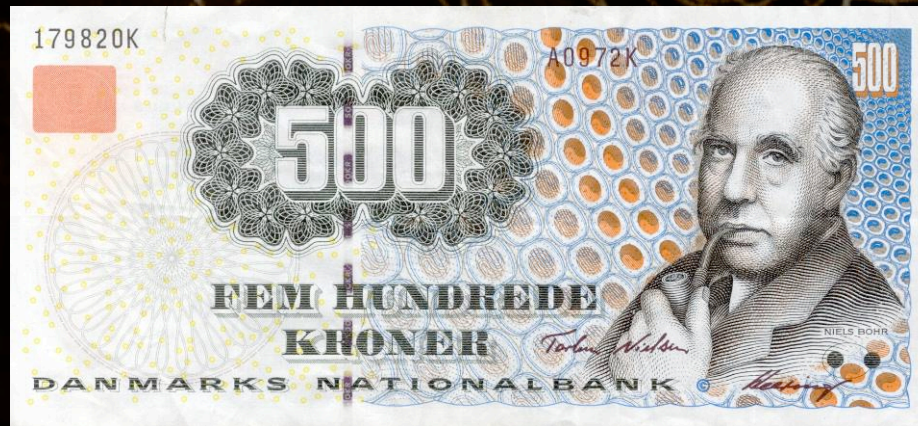


# Atomic Theory

Stockholm, 1922

“The present state of atomic theory is characterised by the fact that we not only believe the existence of atoms to be proved beyond a doubt, but also we even believe that we have an intimate knowledge of the constituents of the individual atoms ...”

Niels Bohr  
(1885–1962)



Current note of 500  
Danish Kroner (DKR)



# Atomic Theory

Today, we even believe that we have an intimate knowledge of the constituents of **nothing**

Vacuum:  
quantum  
fluctuations





# Overview

## ● A journey into the atom

- 1802: Mysterious lines in the Sun
- 1896: Unknown forms of radiation from Uranium salts
- 1897: Discovery of the electron
- Early 20<sup>th</sup> century: the Quantum Hypothesis

## ● The world seen by accelerators

- 1932: the first accelerator
- Fermilab and the “Standard Model”

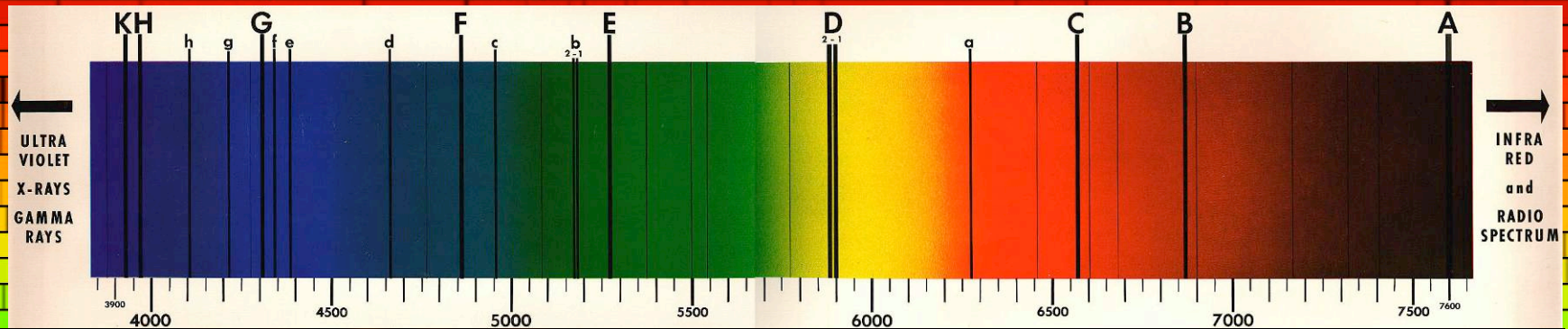
## ● Beyond the known

- Five great questions for your Ask-A-Scientist session





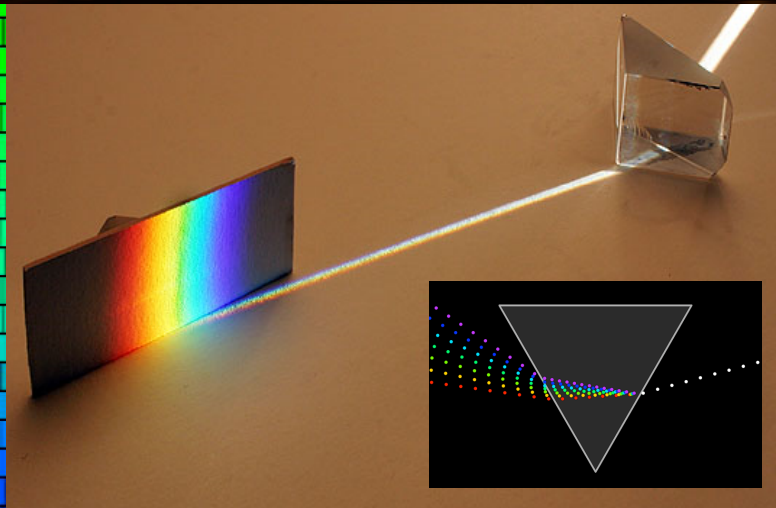
# The trouble with the Rainbow



William H. Wollaston (1802): 7 mysterious holes in the rainbow ...



Wollaston

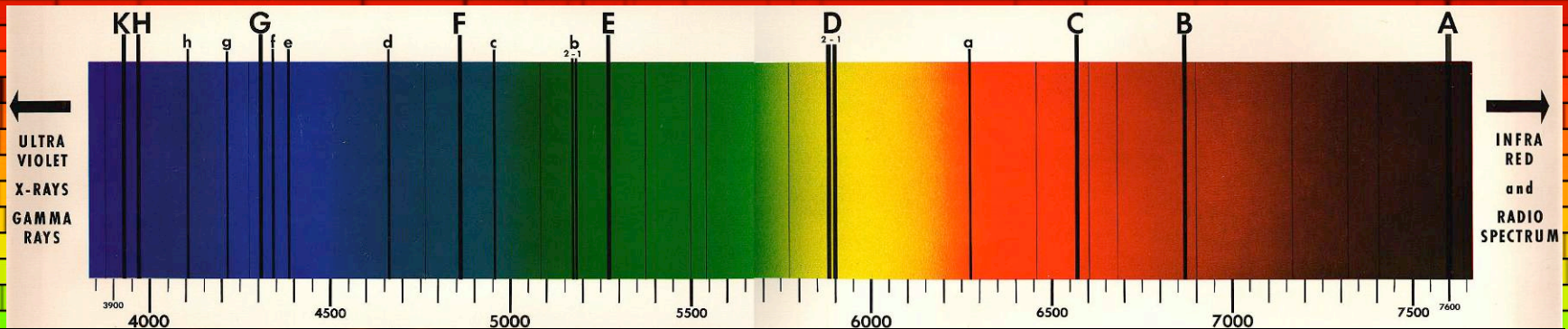


George III

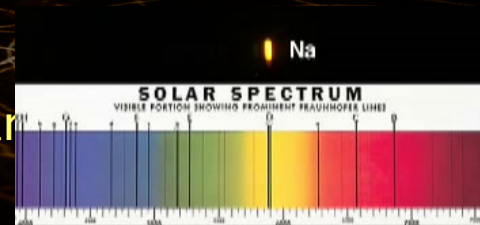




# The trouble with the Rainbow



- William H. Wollaston (1802): 7 mysterious holes in the rainbow ...
- Joseph von Fraunhofer (1821): 500 lines ...
  - Is the Sun made of salt?
- The eclipse of 1868
- A rainbow bridge to touch the stars
  - The birth of spectroscopy!
- 1895: star stuff on Earth



next time you see a street lamp, think back to 1821



Fraunhofer





# 1895: The X Rays



Nun wird man  
dem Teufel  
zahlen müssen

Dec 22 1895



“The Academy awarded the Nobel Prize in Physics to Wilhelm Conrad Röntgen ... for the discovery with which his name is linked for all time: the discovery of the so-called Röntgen rays or, as he himself called them, X-rays. These are, as we know, **a new form of energy** and have received the name "rays" on account of their property of propagating themselves in straight lines as light does. The actual constitution of this radiation of energy **is still unknown.**”

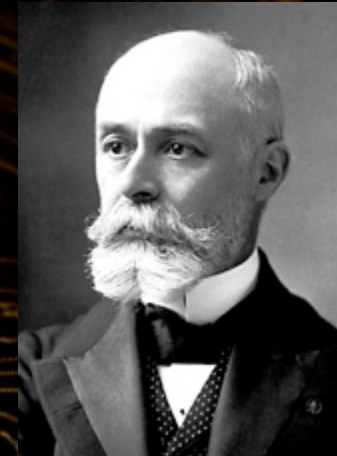
Presentation speech, first Nobel prize, Stockholm, 1901





# Radio Activity

- Becquerel's salts
  - Is there a relation between Röntgen's vacuum-tube induced phosphorescence and natural phosphorescence?
- Pierre and Marie: call it “radioactivity”
- Two hypotheses
  1. An unknown sort of radiation fills all of space. The radioactive elements are the ones that are able to transform this radiation to observable forms





# Radio Activity



PS : Eve Curie's  
"Madame Curie" is  
a must read.

2. "This leads to the supposition that the transformation is more far-reaching than the ordinary chemical transformations, that the existence of the atom is even at stake, and that one is in the presence of a transformation of the elements."

Pierre Curie, Stockholm, 1905

- Helium production + existence of Radium → the alchemists were right!
- Radium becomes more expensive than gold and diamonds





# The Radium Girls

- Radium is a million times more radio-active than Uranium
- 1917–1926: was used in a wide variety of applications,
  - e.g., luminous paint for military watches and instruments
  - Factory girls were encouraged to point the brushes with their lips
  - For fun, they painted their nails, teeth, and even their faces ...



- The body treats Radium like Calcium → stored in the bones
- The right of individual workers to sue for damages from corporations due to labor abuse was established as a result of the Radium Girls case.





# The Fruit of Knowledge

It can even be thought that radium could become very dangerous in criminal hands, and here the question can be raised whether mankind benefits from knowing the secrets of Nature, whether it is ready to profit from it or whether this knowledge will not be harmful for it.

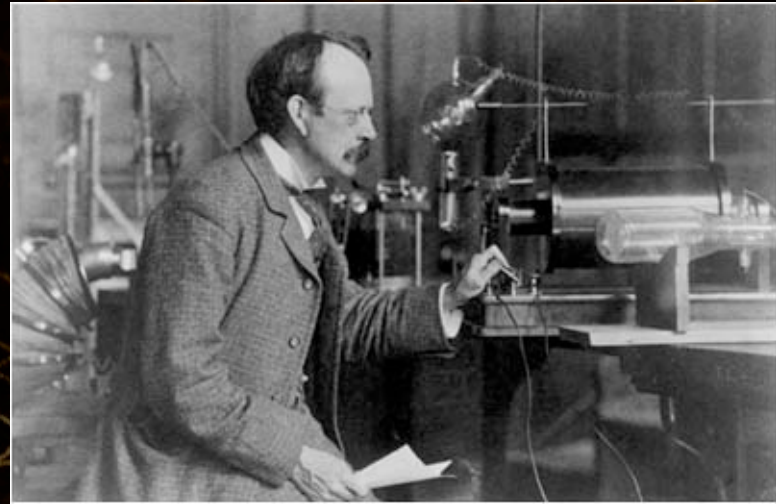
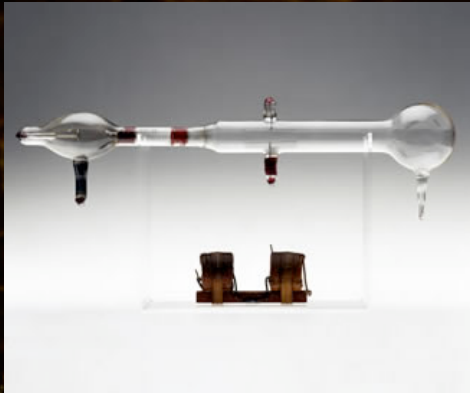
The example of the discoveries of Nobel is characteristic, as powerful explosives have enabled man to do wonderful work. They are also a terrible means of destruction in the hands of great criminals who are leading the peoples towards war.

I am one of those who believe with Nobel that mankind will derive more good than harm from the new discoveries.

Pierre Curie,  
Stockholm, 1905



# A clumsy man



- British or German?
- Deflected by magnetic fields and producing charge accumulation → negatively charged particles?
- Not deflected by electric fields, penetrate thin metals → ether waves?

“Thus the atom is not the ultimate limit to the subdivision of matter; we may go further ... the corpuscles appear to form a part of all kinds of matter ... it seems natural therefore to regard it as one of the bricks of which atoms are built up.”

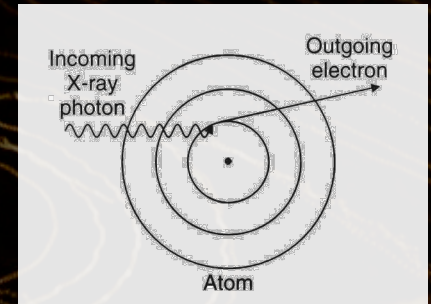
J.J. Thomson, 1897





# Corpuscle of Light

- Classical theory → ultraviolet disaster!
- Planck (1900): equation for black-body radiation with two constants: Avogadro + a new one,  $h$ 
  - Fits with experiment, but ... quanta ... ?
- Einstein (1905): Yes, light quanta!
  - Photo-electric effect → direct proof of the existence of quanta



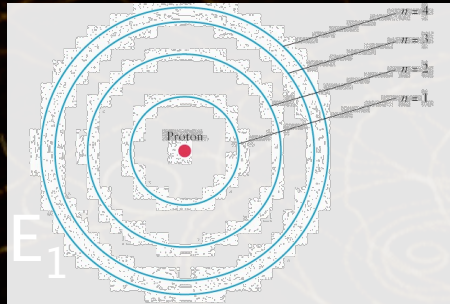
Problems turned to proof:

1. Variation of light **intensity** → variation of electron **numbers**
2. Variation of light **frequency** → variation of electron **energy**



# Wollaston's explanation

- Rutherford's atom + Einstein and Planck's quantum hypothesis → Niels Bohr (1913): There exist fundamentally only separate stationary states in the atoms



- $E_{\text{photon}} = h f = E_2 - E_1$

- Applied to kitchen salt and sunlight, Wollaston's rainbow, now 100 years old, was finally explained
- But what a strange explanation ...





# The Language of Atoms



Niels Bohr  
(1885–1962)

- Correspondence
  - From quantum mechanics, the classical laws must be obtained in the limit of large quantum numbers or small  $h$
- Complementarity
  - Mutually exclusive descriptions must be accepted. An experiment can show particle-like properties of matter, or wave-like ones, but not both at the same time.



# The Copenhagen Interpretation

- The wave function only describes a (subjective) state of knowledge; it is not itself “real”
  - Schrödinger’s cat can easily “be” both alive and dead
  - Wigner’s friend can see a different wave function than Wigner
  - EPR is not a paradox. Wave function collapse is subjective. Cannot be used to transfer information at  $v > c$  anyway (God doesn’t play dice?)
  - The uncertainty principle defines the limits of certainty
- Science is only about predicting the outcome of experiments. Additional questions are meta-physical (positivism)
  - So the wave function is all you’re going to get
- Paraphrasing : “Shut up and calculate”

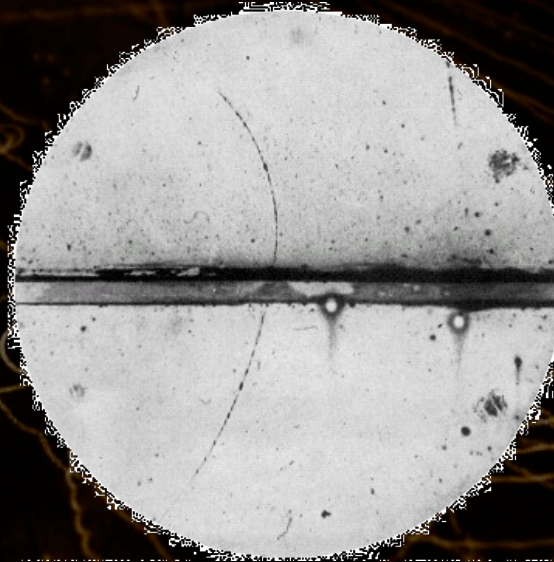
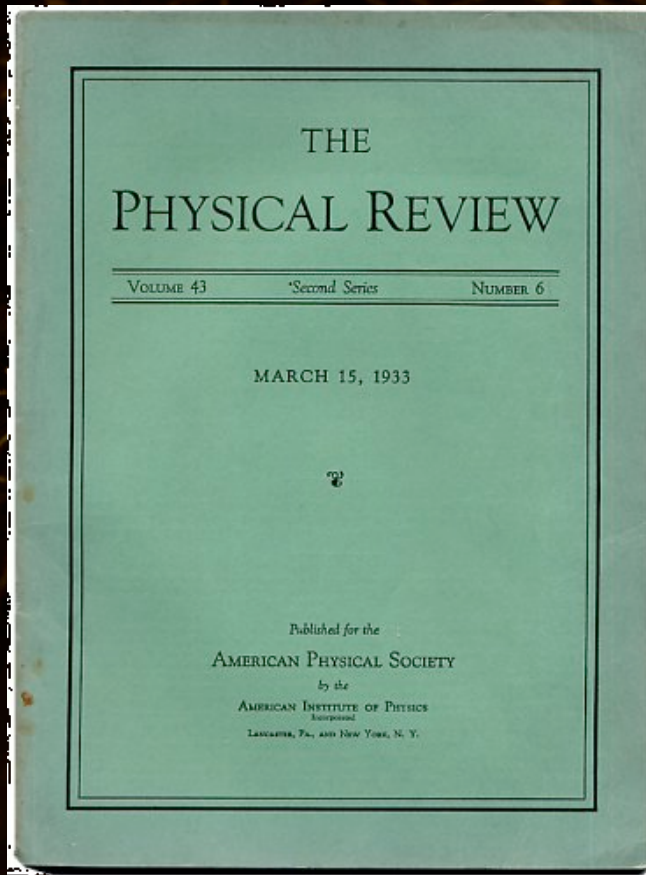




# Antimatter

- Dirac's relativistic wave equation with spin  $\rightarrow E^2 =$

...



Carl  
Anderson  
(1905–1991)

"On **August 2**, 1932 ... the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence [...] of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron"

C. Anderson, "The positive electron", Phys. Rev. 43 (1933) p.491

A Quantum Journey –

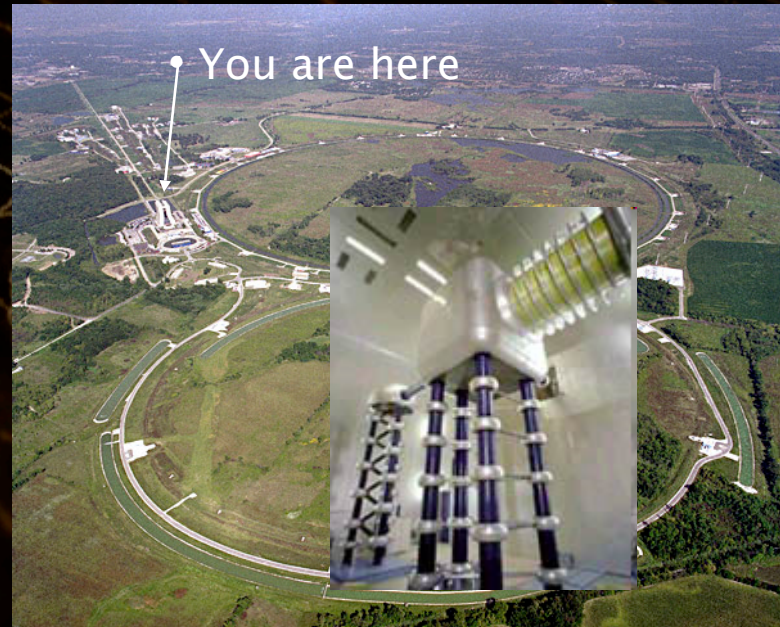
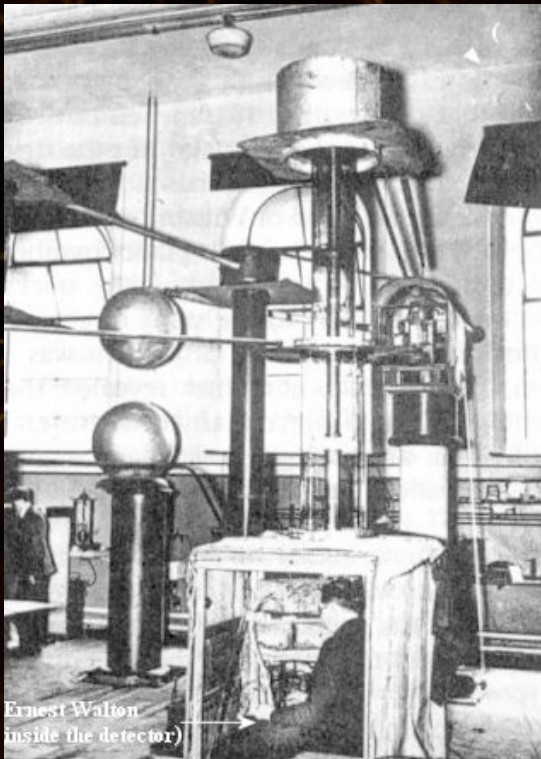




# The World Seen by Accelerators

- 1932: Cockcroft & Walton built a system that could fire protons, like bullets, into metal targets:  $p + \text{LiF} \rightarrow \text{Be}, \text{He}, \text{O}, \dots$

Cavendish laboratory, ca. 1932



Fermi Laboratory, ca. 2000

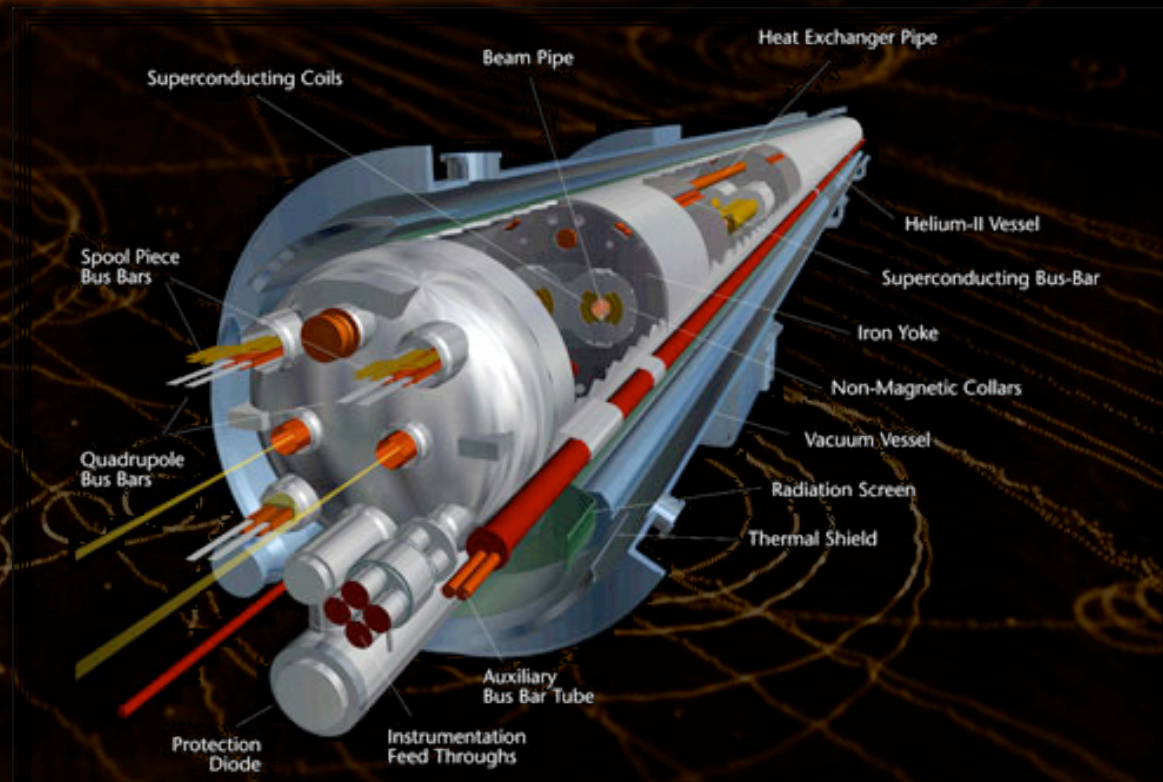
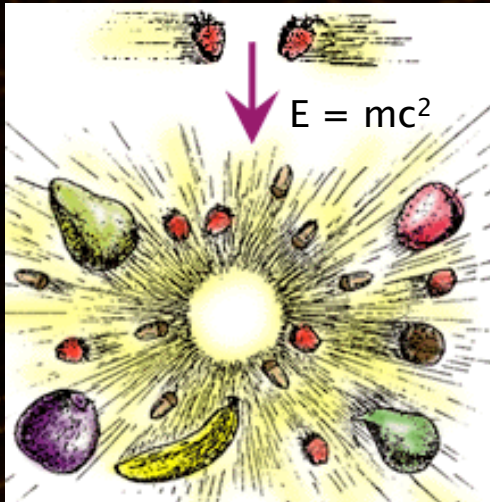
(1951): “Transmutation of atomic nuclei by artificially **accelerated** atomic particles”





# Particle Accelerators

- The goal:

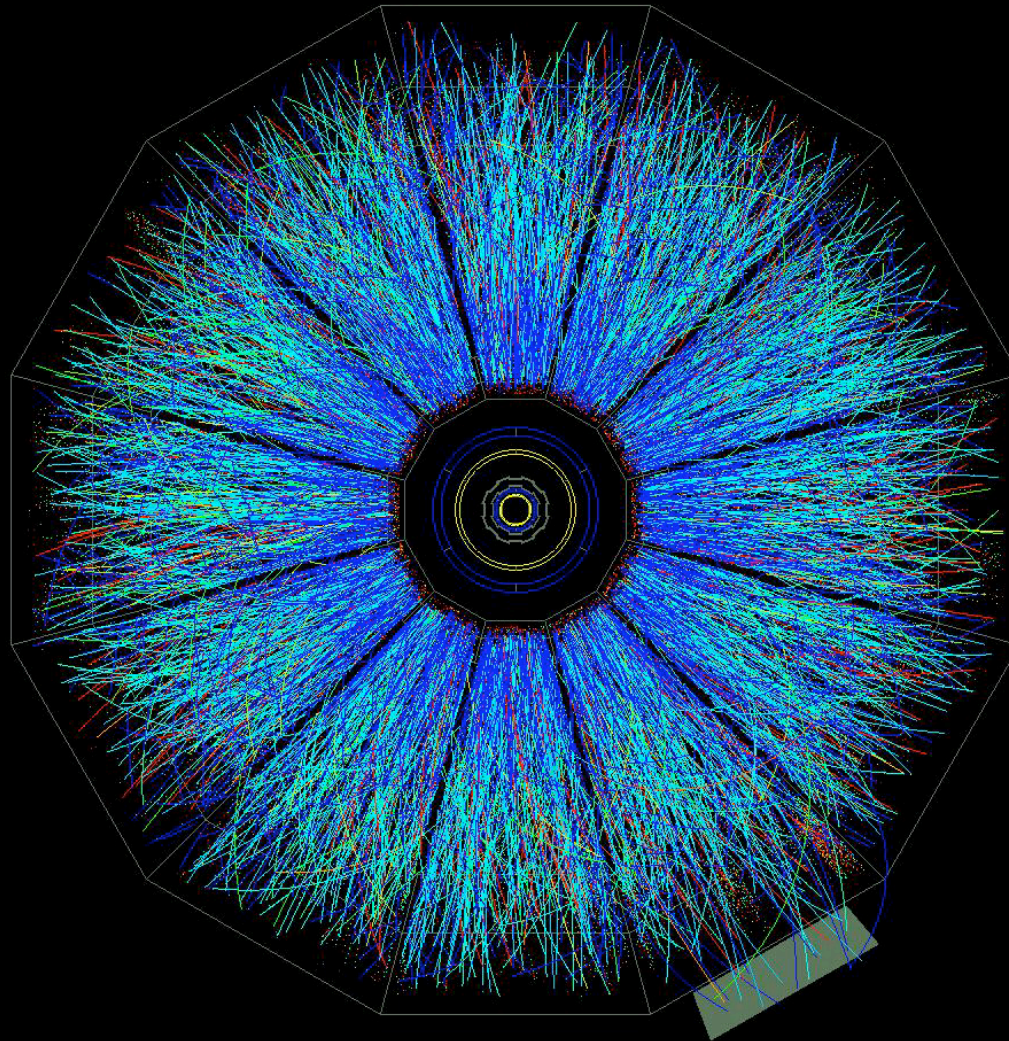


- Accelerators are ‘optical’ systems, with
  - Light → charged particles
  - Wave length shortening → particle acceleration
  - Lenses → magnets





# Collisions





# Detectors

- Tracking

- Trace the path of a particle as it's zipping through

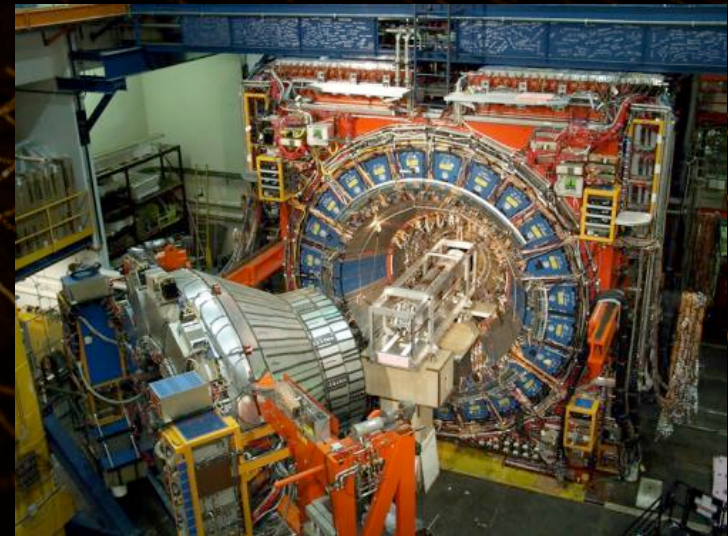
Thomson used a fluorescent screen which gave off eerie light when hit by electrons. Röntgen used photographic plates

- Calorimetry

- Let a particle 'hit' something and get a signal proportional to the total energy it had

- Particle identification

- Muons are highly penetrating
- Hadrons are more penetrating than electrons and photons
- Photons aren't charged so don't leave tracks, electrons do
- ...



The CDF detector at Fermilab

We use combinations of multiple devices, arranged in an onion-like structure so that the least 'interfering' measurements are carried out first



# The Tevatron at Fermilab

- Relative to combustion of 1 kg of octane molecules (gasoline)

...

- 100m Waterfall : 0.000 025
- Burning wood : 0.3
- Burning sugar (metabolism) : 0.5
- Burning ethanol or coal : 0.75
- Burning Beryllium : 1.5
- Uranium-235 fission : 2 000 000
- Deuterium-Tritium Fusion : 10 000 000
- Matter-Antimatter Annihilation : 2 000 000 000
- Tevatron collisions : 2 000 000 000 000

- Still, Dan Brown exaggerated a bit in Angels & Demons ...

- “If all of the antimatter ever produced at Fermilab had been collected, we would have a couple of nanogrammes ...”

Dave Vandermeulen,  
antimatter expert, Fermilab

**The Power of  
Antimatter**  
**Dr. Marcela Carena**  
**Fermilab and U Chicago**  
**Thursday, May 21, 2009**  
**@ 8 Tickets \$5**





# Beyond the Known

“There are more things in heaven and earth, Horatio,  
than are dreamt of in your philosophy.” Hamlet (act I,  
sc. v)

- What is it that produces the special concentration of energy around particles known as ‘mass’?
- What is ‘Dark Matter’? Can we produce it?
- What about ‘Dark Energy’?
- How does gravity fit in? Are all forces one?
- Are there undiscovered principles of Nature? What physical laws exist beyond the known?





# Mass

- Consider an ether 'field' distributed evenly across the Universe, of uniform strength
- Suppose that different particles experience this field as being more or less transparent, i.e. that different particles couple to it with different strength
- Suppose that the nature of the interaction is such that the ether 'condenses' around particles which couple to it, causing an increased energy density around the particle
- This is essentially the Higgs mechanism



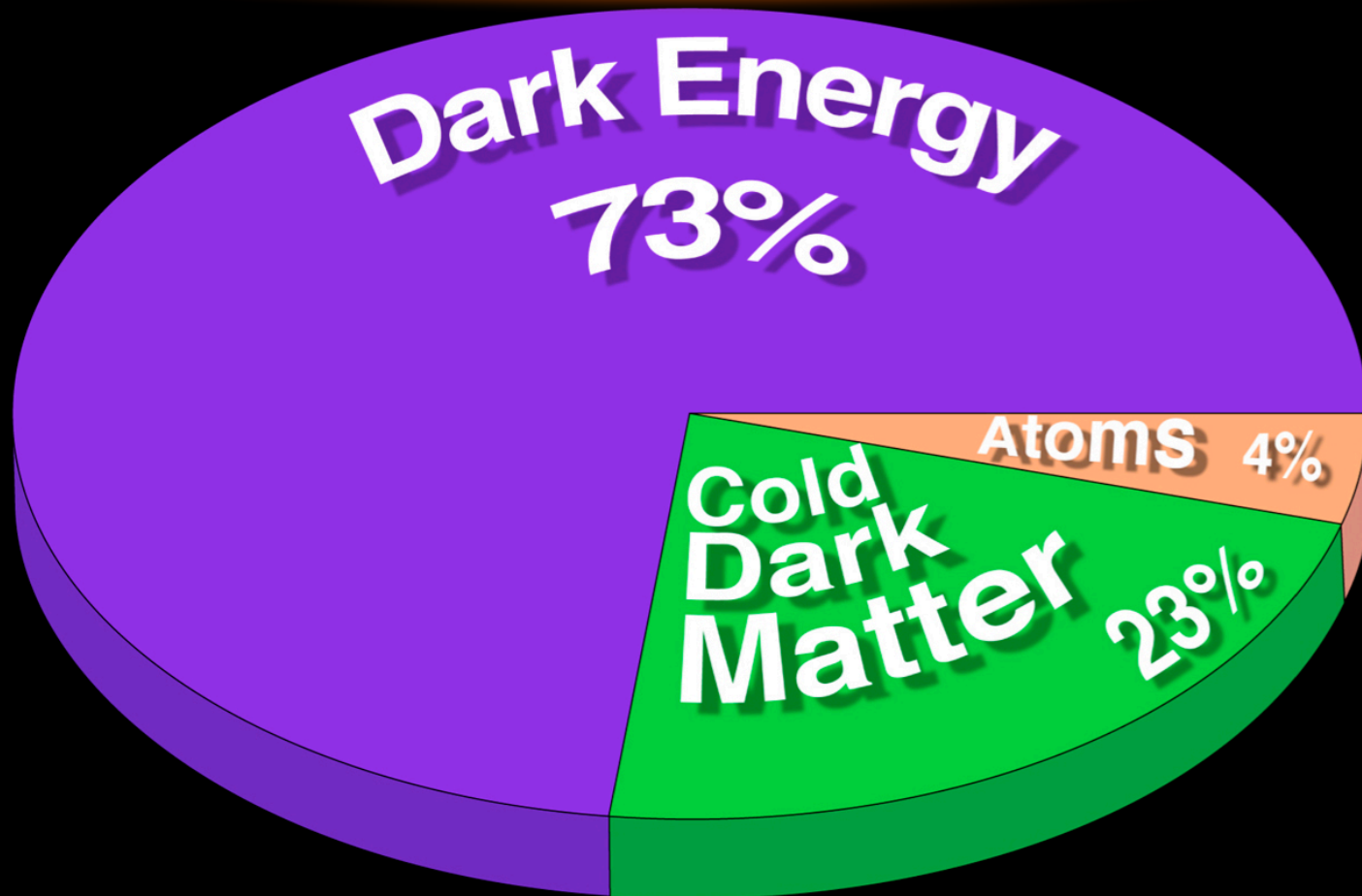


# The Higgs Particle

- If correct, the Higgs mechanism makes one spectacular prediction: it should be possible to excite a wave in the Higgs field itself, an ether wave
- This wave would quickly dissolve (decay) into massive particles, but should be detectable via its decay products
- Made out of pure 'Higgs' ether, in particle form this wave is known as the 'Higgs particle' or 'Higgs boson'
- We are searching intensely for it here at Fermilab, but so far it has remained elusive



# The Composition of the





# Dark Matter

- August 2006: Clowe et al.: “A direct empirical proof of the existence of dark matter”

Astrophysical Journal 648 L109–  
L113 (2006)





# The Undiscovered Country

## ● Open-minded “model building”:

Matter

- There could be new fundamental matter
- “Fundamental” matter might be composite

Force

- There could be new fundamental forces
- Known forces might not be fundamental
- What is gravity, at the fundamental level?

Spacetime

- There could be new symmetries of space and time
- Known symmetries might break down
- There could be extra dimensions





# What can we say beforehand?

Matter

Force

Spacetime

- A] A complete theory should:
  - agree with all measurements so far
  - explain the origin of mass
  - explain dark matter and dark energy
  - Q: explain neutrino masses
  - Q: address the hierarchy problem
  - incorporate quantum gravity
- B] A complete theory could:
  - involve grand unification (we have hints of it)
  - involve measurable new physics in the near future
  - be aesthetic and natural
  - be simple



# A Natural Cause

We glibly talk  
of nature's laws  
But do things have  
a natural cause?

Black earth turned into  
yellow crocus  
Is undiluted  
hocus-pocus



P. Hein, friend of Niels Bohr

